

CADRE/PC 2005-012

AIR FORCE FELLOWS (SDE)

AIR UNIVERSITY

“ASYMMETRIC FAST TRANSIENTS”

APPLIED TO

REDUCE DOD ACQUISITION CYCLE TIME

by

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A Research Report Submitted to Air Force Fellows, CADRE/AR

In Partial Fulfillment of the Graduation Requirements

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CADRE/AR

Maxwell Air Force Base, Alabama

April 2005

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE APR 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE 'Asymmetric Fast Transients' Applied to Reduce DOD Acquisition Cycle Time				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air University,Air War College,325 Chennault Circle,Maxwell AFB,AL,36112				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 59	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

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Preface

This research was accomplished under the Air Force Fellows National Laboratory Technology Fellowship. During the fellowship, I worked on a team applying an innovative reliability methodology to the B61 modification 7 and 11 (B61-7, -11) Life Extension Program (LEP). This research has value for the Department of Defense (DoD) Acquisition Process because it recommends a new approach to Agile Acquisition and documents a methodology to calculate reliability prior to testing, which may be able to reduce acquisition cycle time.

I'd like to acknowledge the guidance provided by research advisor, Col Steven Suddarth. Col Suddarth is the USSTRATCOM National Laboratory Liaison, but graciously agreed to be my research advisor, having just moved from the Air War College faculty. I'd also like to thank the B61-7, -11 reliability team leader Dr. Jane Booker, and the team members Dr. Karen Hensch, Dr. Timothy J. Ross, Dr. Dean L. Sanzo, Dr. Brian G. Scott, and Mr. Gerald Schotik. In support of my technical fellowship, Mr. Schotik also provided countless explanations of nuclear physics and chemistry, as well as key insights on probability theory. The support of Air University's CADRE office, Ms. Dee Taylor, and AF/XOS-N, Mr. Dave Court, also proved invaluable.

Abstract

The need to implement a truly agile acquisition process is apparent. Current acquisition professionals are required to brief decisions through the chain of command using a lengthy process to execute a change in direction. Truly agile organizations create what John Boyd called “asymmetric fast transients” in order to maneuver inside the enemies’ or competition’s decision cycle. Our warfighting doctrine calls for trust and initiative to enable all levels of leadership to seize the initiative when opportunities present themselves. This research presents the need for development of acquisition doctrine that takes the same approach in executing acquisition programs. To this end, an innovative tool DoD should consider to reduce risk and shorten acquisition cycle time is the Performance and Reliability Evaluation with Diverse Information Combination and Tracking (PREDICT) reliability methodology.

How can PREDICT help the acquisition process to be more agile when numerous acquisition reform efforts of significant scope have tried and failed? The unique contribution of PREDICT is using formal elicitation of expert knowledge to calculate concept reliability prior to testing. Statistical analysis of the expert knowledge yields a calculation of reliability and uncertainty of the technology or concept. PREDICT is supporting the Los Alamos National Laboratory (LANL) mission of maintaining and certifying the safety and reliability of nuclear weapons without system testing. For DoD,

this could provide a completely alternative methodology for determining technology readiness levels and risk, before launching an acquisition effort.

This research will explain the PREDICT process, and then show how its application in the DoD acquisition process could provide the following benefits:

- Shorten the Technology Planning Integrated Process Team (TPIPT) and Modernization Planning processes.
- Enable assessment of reliability for new concepts at Milestone A and for legacy systems undergoing change, eliminating unproductive paths earlier.
- Optimize test planning and execution by showing testing impact to reliability.
- Enable transfer of knowledge as experienced personnel transition out of programs.

A classified Los Alamos report will document the results of the PREDICT reliability calculation for the B61-7, -11. Because of “need to know,” access to the classified report will be determined on a case-by-case basis after the initial reliability estimate is completed in the fall of 2005. A LANL point of contact (POC) is listed in Appendix D.

Chapter 1

Introduction

The greatest challenge to any thinker is stating the problem in a way that will allow a solution.

—Bertrand Russell

Is there a problem with the DoD acquisition process? The answer is without a doubt, yes. The process takes too long and is too expensive. Consider the F/A-22 and the Space Based Infrared Satellite (SBIRS) weapon systems which were on the drawing board when the author entered the Air Force in 1986 – 19 years ago! The F/A-22 began as the Advanced Tactical Fighter in 1984.¹ Likewise, SBIRS began in 1984 as a portion of Ballistic Missile Defense called the Boost Surveillance and Tracking System.²

Both of these programs have a track record of tremendous delay and cost growth. In 1991 the Air Force planned to purchase 648 F-22s for \$86.6 billion. In September 1993, after the Bottom Up Review, the F-22 purchase quantity was changed to 442 for \$71.6 billion.³ This was a 31 percent production quantity reduction, but only a 17 percent reduction in cost. Continuing this trend over a number of years, numerous technical and production issues, as well as three Congressional budget cuts led to a more recent estimate of \$69.7 billion for 276 aircraft.⁴ This equated to a 2.6 percent cost reduction, but a 38 percent reduction in quantity. While the total cost of the program is capped by Congressional restriction, the per-unit cost has increased dramatically. Similarly, SBIRS-

High, the early warning portion of SBIRS, went from an estimate of \$1.9 billion in 1996, to an estimated \$4.5 billion in late 2001.⁵ Ironically, these examples of DoD acquisition programs occurred during a time of acquisition reform, including high-profile efforts such as the Lighting Bolt initiatives and the elimination of military specifications.

The latest acquisition reform push is Agile Acquisition. The five pillars of Agile Acquisition are Collaborative Requirements, Technology Transition, Seamless Verification, Robust Systems Engineering, and Expectations Management.⁶ A review of the five pillars reveals nothing revolutionary that if fully implemented would have reduced the cycle time for the F/A-22 or SBIRS from 20 to 5, or even 10 years. For example, Robust Systems Engineering calls for designs that are “insensitive to variability in manufacturing and use.”⁷ This implies exceeding the operational requirements specified by the user. Unfortunately, the opposite is usually the case – the user is normally asked to relax requirements in order to reduce cost or meet production schedules. Also under Agile Acquisition, the Air Force is realigning Program Executive Officer (PEO) positions. Two PEOs are moving to Product Centers to be co-located with their program offices.⁸ These realignments are good and will likely result in marginal reductions in cost and cycle time, but nothing on the order of a factor of two or four, as needed. What is needed is a revolution in acquisition affairs, not continued Band-Aid fixes.

How does DoD move from achieving marginal reductions in cycle time to cutting cycle time in half or more? One thing not to do is to keep making adjustments to the current system. In “Certain to Win” Chet Richards explains the result of partial fixes, “You won’t get there by trying to do the same stuff, only faster. What you’ll get is a

mess...⁹” Despite the success of our fielded forces, it’s hard to argue from a cost and cycle time perspective that the DoD acquisition process is not a “mess.” A good assessment of what has occurred is described in Lt Col Steven Suddarth’s “Solving the Great Air Force Systems Irony.” Suddarth contends the acquisition bureaucracy has evolved over a period of 35 years from the “...simple management of complex systems to the complex management of simple ones.”¹⁰ Why has this evolution toward complex management systems occurred?

The acquisition disasters of the 1970s and 1980s are typified by the example of the A-12, or on a smaller scale, the \$500 toilet seat or hammer. The A-12 Avenger II was a Navy stealth fighter that was cancelled in January 1991 because of materials issues that had driven per unit cost to \$165 million.¹¹ Ironically, the F/A-22 has risen to \$250 million per aircraft, if 276 units are produced for \$69 billion. One reform effort after another led to tighter controls on decision-making and increased documentation. Documentation does not facilitate communication. Conversely, Richards states, “...explicit forms are often used not to communicate but to document, not to inform but to protect oneself.”¹² Richards states mutual trust is critical to encouraging individual initiative. The institutional lack of trust in the DoD acquisition process has erased individual initiative. The Agile Acquisition initiative is a step in the right direction, but it appears it may only be “trying to do the same stuff, only faster.” How do we get out of the rut of making marginal improvements to a process that has delivered winning warfighting capability, but takes too long and is too expensive?

Trust and initiative are critical. Process and documentation have slowed the DoD acquisition process to the point where technology proliferation through media such as the

Internet may enable our adversaries to apply and field leap-ahead technologies before we can. To avoid this scenario, chapter two discusses the origin of the Observe Orient Decide Act (OODA) Loop decision process and how it can be applied in DoD acquisition to enable our acquisition professionals to seize the initiative. The idea of creating Acquisition Doctrine and an Acquisition Battlelab for special training and experimentation are presented. Chapter two introduces the PREDICT reliability methodology and discusses how a modified PREDICT methodology could improve the technology development and modernization planning processes. Chapter three briefly provides a number of other potential DoD acquisition applications of PREDICT. An example of how industry (Delphi Automotive) applied and validated the PREDICT methodology is provided in chapter four.

The appendixes provide a background on reliability theory, a more detailed description of the PREDICT process, and a mock example of applying the PREDICT reliability methodology. Appendix D lists a LANL POC for requesting access to the classified report which will document of the use of PREDICT on the B61-7, -11.

Notes

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² O'Neill, Malcolm R., Lt. Gen, USA (Director, Ballistic Missile Defense Organization), "Ballistic Missile Defense: 12 Years of Achievement." Statement to the House National Security Committee, April 4, 1995. Defense Issues: Volume 10, Number 37. On-line. Available at: <http://www.defenselink.mil/speeches/1995/t19950404-oneill.htm>, 13.

³ F-22 Raptor History, GlobalSecurity.org, 8 Mar 05. On-line. Available at: <http://www.globalsecurity.org/military/systems/aircraft/f-22-cost.htm>.

⁴ F-22 Raptor Cost, GlobalSecurity.org, 8 Mar 05. On-line. Available at: <http://www.globalsecurity.org/military/systems/aircraft/f-22-cost.htm>

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⁵ Richelson, Jeffrey T., "The Satellite Gap." *Bulletin of Atomic Scientists*, January/February 2003, (vol. 59, no. 01). On-line. Available at: http://www.thebulletin.org/article.php?art_ofn=jf03richelson, 4.

⁶ Agile Acquisition, ACE CONOPS, SAF/AQ & AFMC/CC, 2 March 04. On-line. Available at: http://ax.losangeles.af.mil/axd/agile_acq/agile_acq.htm, 1.

⁷ Ibid.

⁸ Agile Acquisition: Air Force PEO Realignment Take Major Steps Forward, FindArticles, On-line. Available at: http://www.findarticles.com/p/articles/mi_m0QMG/is_2_33/ai_n6005568, 1.

⁹ Richards, Chet, *Certain to Win: The Strategy of John Boyd, Applied to Business*. Xlibris Corporation, www.Xlibris.com, 2004, 166.

¹⁰ Suddarth, Steven C., Lt Col, USAF, "Solving the Great Air Force Systems Irony," 25 Mar 02. On-line. Available at: <http://www.airpower.maxwell.af.mil/airchronicles/apj/apj02/spr02/su...>, 2.

¹¹ Wikipedia, A-12 Avenger II, 1 Apr, 2005. On-line. Available at: http://en.wikipedia.org/wiki/A-12_Avenger_II.

¹² Richards, 120.

Chapter 2

OODA Loop

Agility: The ability to change one's orientation – roughly, worldview – in response to what is happening in the external world.

—John Boyd¹

Reducing DoD acquisition cycle times by a factor of two or more will only occur through a revolution in acquisition affairs. The acquisition corps must be equipped to seize the initiative when opportunities arise. Consider an Army company commander in the ground war during the Gulf War or the War in Iraq (4 days and 3 weeks long, respectively). These officers were trained to follow their “Commander’s Intent,” seize the initiative, move around obstacles, and push on to accomplish their mission. Imagine these officers having to rewrite their operations orders and brief the changes up the chain of command if they decided to take hill B versus hill A (as planned) to accomplish their mission. Just like a pilot switching from a primary target to an alternate, these officers’ judgment is trusted and the command and control systems are in place for the changes in plans to be seamlessly executed. Modern-day warfighters make decisions on the fly, keeping the enemy off balance.

In acquisition, time is the enemy. Why not equip the acquisition professional with a process and the communication tools necessary to restore trust and enable them to seize

the initiative? Applying the concepts of war to the business environment is not unheard of.

Asymmetric Fast Transients

In “Certain to Win,” Richards applies Col John Boyd’s OODA loop concept to business. In the 50’s Boyd developed the “Aerial Attack Study” which showed in aerial combat for “every maneuver there is a series of counter maneuvers.”² Essentially the same concepts are still taught to fighter pilots all over the world. Col Boyd is credited with designing the maneuvering specifications for the F-16 and F-18.³

Boyd’s OODA loop concept grew out of his study of the F-86 advantage over the MiG-15 in the Korean War. Despite the nearly equal performance characteristics, the F-86 had a ten-to-one victory ratio over the MiG-15. Boyd agreed pilot training was better for the F-86, but that “energy maneuverability” was the driver for the lopsided record. Despite the MiG-15’s tighter turning ability, the F-86’s bubble canopy provided better visibility, and the F-86’s full power hydraulic controls enabled quicker aircraft response. These two factors created what Boyd called “asymmetric fast transients.”⁴ Note this did not mean executing the same maneuvers quicker. This concept refers to transitioning from one maneuver to a completely different or unexpected maneuver, quicker than the enemy can react. Applied to business or acquisition, this means avoiding the “same stuff, only faster” improvement mentality and shifting to creating the ability to quickly make an abrupt change into an entirely new direction.

Experience shows once a concept and acquisition strategy to field a warfighting capability is in place, it’s like shifting the orbit of a planet to transition to a new

approach. Say, for example, the program manager (PM) runs into a technology roadblock. The PM should be able to immediately “maneuver” around that technology with other approaches to field the capability. Likewise, if the PM recognizes a technology that provides a shorter path to the capability, he or she should be able to “seize” the initiative and pursue it. This level of trust and personal initiative needs to be reinserted in the acquisition process. This should be the goal of Agile Acquisition.

How do we evolve the acquisition process back to a simple process managing complex systems? Project engineers, PMs, and program directors need to be enabled to create “asymmetric fast transients.”

BLU-118/B

A good example of a team that was enabled in this manner is the team that developed and fielded the BLU-118/B Thermobaric Weapon. On 11 Oct 01, the Defense Threat Reduction Agency organized a quick-response team including Navy, Air Force, Department of Energy (DOE), and industry. Their purpose was to look at a number of on-going Advanced Concept Technology Demonstrations and then “identify, test, integrate, and field a rapid solution that would enhance weapons options in countering hardened underground targets.⁵” The Navy focused on development of the new explosive, while the Air Force had system integration, safety and flight, and a modified fuze. On 14 Dec 01, the BLU-118/B was successfully tested at a Nevada Test Site tunnel. On 21 Dec 01, Undersecretary of Defense for Acquisition, Edward C. Aldridge, announced a small number of the weapons were being deployed to support the war in Afghanistan. In late January 02, the Air Force completed technical data and flight

certifications, clearing the way for operational use of the ten warheads that were available. The first combat use of the warhead occurred on 3 Mar 02.⁶

The team was formed in mid-October and ten warheads were available for use at the end of January – approximately three and half months later. The team created an “asymmetric fast transient” by modifying an existing penetrator with new capability to reach the enemy where previously they had been safe. The compressed process employed on the BLU-118/B initiative should be the rule, instead of the exception. It should not take actual combat for the acquisition community to shift into high gear. Whether we are at war or not, every delay drives two major impacts: 1) the capability delayed is not available for use in the field, and 2) resources for addressing other warfighting capabilities are not available.

Acquisition Doctrine

Our vision should be to field the warfighters’ needs for the Global War on Terrorism (GWOT) in the shortest cycle time possible. Time wasted on twenty-year long acquisition efforts could very well equate to lives lost. The time has come for the development of Acquisition Doctrine to guide the equipping and training of the acquisition corps for Agile Acquisition. A first step should be the formation of an Acquisition Battlelab. Here an initial cadre of special acquisition forces could attend the acquisition equivalent of the “weapons” school. The focus should be on fielding technologies to meet the Combatant Commander’s highest priority shortfalls in prosecuting the GWOT. Acquisition cycle times of one month, one year, or five years for more complex efforts should be the norm. In parallel, this Acquisition Battlelab would

be responsible for developing the Acquisition Doctrine of fast cycle times and planning the transformation of the entire acquisition corps in ten years.

OODA Loops and Planning

At the Air Force major command (MAJCOM) level, experts from the Air Force Research Lab (AFRL), the Product Centers, Combatant Commands, System Program Offices, and industry support a two-year modernization planning process. The output of this process, at least for Air Force Space Command (AFSPC), is a Strategic Plan which supports the development of their Program Objective Memorandum (the six-year plan for funding operations and acquisition). Note that AFSPC experimented with a one-year process, but is likely returning to a two-year process. The MAJCOMs use different terms for the process including strategic planning, the modernization planning process, and the integrated planning process. The latest term for Air Force level strategic planning is the Capabilities Based Planning process. Although there are different names, the goal is to identify capabilities to fill the gaps in warfighting ability.

AFRL and the Product Centers support MAJCOM modernization planning with their TPIPTs. The TPIPTs, in cooperation with industry, attempt to answer the question of how technology can be used to fill gaps in military capability. According to Dr. (Lt Col) Russ McNutt, the TPIPTs process is broken – too many people involved and it takes too long.⁷ The process needs large numbers of people to meet numerous times over the course of two years in their effort to write technology development plans.

However, participation is limited, at least for the modernization planning process (based on the author's personal experience). Essentially what occurs is a small group ends up doing the very best they can with limited input from the numerous stakeholders.

No “stick in the eye” is intended – tightened travel budgets and personnel reductions have a major impact on these types of long-term travel intensive planning efforts. Two years is an unacceptable cycle for developing technologies and concepts to fight the GWOT. Most importantly, a two-year planning cycle very likely puts the terrorist inside our planning OODA loop. How could this two-year cycle be reduced by a factor of two, or perhaps, four?

Expert Input

Tremendous expertise resides in DoD and industry. As mentioned above, a key problem in the planning process is participation by the experts. How do you harness this expertise and bring it together? The appendixes of this research describe in detail and provide an example of a methodology LANL is using to formally elicit and quantify expert judgment to calculate concept reliability for nuclear weapons prior to testing. The methodology is called PREDICT – Performance and Reliability Evaluation with Diverse Information Combination and Tracking. PREDICT is defined as a “set of formal, structured techniques for eliciting, quantifying, and analyzing an often-undocumented asset: the knowledge that resides with a company’s designers, engineers, and scientists.”⁸ For LANL, the issue was calculating reliability early, during the concept phase, and quantifying reliability without a system test. For DoD, the PREDICT methodology could be adapted to implement virtual TPIPTs (VTPIPTs) and virtual modernization planning efforts, eliciting expert knowledge from participants spread out across the country.

Modified PREDICT Methodology

Informed decision-making when little data / information is available is key. At LANL, the team was on-site and participated on a non-interference basis (with their primary duties) over a long period of time. The author participated for eight months on the PREDICT team that met twice a week for one and a half hour elicitation sessions with the scientists and engineers that designed the changed components for the LEP of the B61-7, -11. For LANL, reliability of changes to existing weapons is key. These weapons cannot be tested at the system level, so a detailed and somewhat lengthy process is employed to ensure reliability. A thorough discussion of reliability theory and the PREDICT process are provided in Appendix A and B, respectively. The essence of PREDICT is a common sense step-by-step methodology for rigorously extracting (eliciting) knowledge from subject matter experts (SMEs) and then quantifying the data so decision-makers can make informed decisions.

The key application for DoD is recognizing the value of analyzing expert knowledge to aid decision-making. A critical issue in technology development for the TPIPTs is understanding the maturity of a given technology. A modified PREDICT methodology could be used in the TPIPTs process to better characterize technology maturity and draw in greater participation.

VTPIPT

Establishing a VTPIPT would not be “doing the same stuff, only faster.” This would be a completely new direction. Consider a team of recognized military, government civilian, and academic experts in a specific mission area / technology. Using networking

technologies, the core TPIPT would elicit information by electronically sending out their requests for information on technology concepts that could fill gaps in military capability. Instead of traveling to meetings, these experts would reply electronically. Memorandas of Agreement would establish expectations for response with government experts – message boards and websites would facilitate flow of information. Academic experts would be on contract to reply within a specified time. The core team would minimize bias by using the Delphi method. With the Delphi method, the experts submit ideas independently. In a group setting, personality and position can easily bias a decision. With a VTPIPT, replies to questionnaires (elicitations) would be independent between the submitters. As the core team synthesizes the data, subsequent rounds of questionnaires would update everyone on the good ideas received, so the entire team could see and comment on the progress of the analysis.

Trust

The entire focus of any DoD use of the PREDICT process should be to create “asymmetric fast transients” to speed up the acquisition OODA loop. To do so, lower level acquisition leaders need to be able to make decisions and move out, without having to go through the enormous briefing and documentation burden currently required. In war, leadership at the strategic, operational, and tactical level is trusted to make life or death decisions that affect the outcome of the mission. In the current DoD acquisition process, leadership is not trusted, the process is.

PREDICT is one of potentially many decision tools the Acquisition Battlelab should experiment with to reduce cycle time. Success should be evaluated based on significantly reducing the time from when the warfighter identifies the need to when the solution is in

hand to fill the gap in military capability. Other tools should eventually be employed for all levels of the acquisition process. Again, the complex processes in place evolved over 35 years. Twenty years of acquisition reform has resulted in twenty year cycle times for major systems. The Acquisition Battlelab should be chartered to continuously experiment with technology and processes to reduce cycle time and to develop acquisition doctrine to guide the training and equipping of our acquisition professionals.

Trust and initiative need to be reestablished at all levels so opportunities can be seized at the earliest point. If a PM wants to make a change in direction, ideally a communications capability should be in place to make the notification and get the green or red light from the chain of command within minutes or hours. Notification levels could be established which would correspond to the tactical, operational, or strategic level of acquisition. Establishing guidelines for these levels of acquisition would facilitate deciding how high up the chain of command a given decision needs to go. While the BLU-118/B example was a rather straightforward non-complex effort, the team must have established streamlined communications methods to keep the effort on track. Whether on land, sea, or in the air, our fighting doctrine is centered on seizing the initiative and maneuver at all levels of war. Similar doctrine should be developed for DoD acquisition to support decision-making for significantly reduced cycle times.

Chapter three looks at other potential applications of PREDICT in DoD acquisition including how PREDICT's emphasis on expert knowledge fits well with Knowledge-Based Acquisition.

Notes

¹ Richards, Chet, Certain to Win: The Strategy of John Boyd, Applied to Business. Xlibris Corporation, www.Xlibris.com, 2004, 29.

² Coram, Robert, John Boyd – USAF, The Fighter Pilot Who Changed the Art of Air Warfare, The Aviation History On-Line Museum, 2002. On-line. Available at: <http://www.aviation-history.com/airmen/boyd.htm>.

³ Ibid, Coram.

⁴ Richards, 60.

⁵ Pike, John, BLU-118/B Thermobaric Weapon, GlobalSecurity.org, 12 March, 2005. On-line. Available at <http://www.globalsecurity.org/military/systems/munitions/blu-118.htm>.

⁶ Ibid, Pike.

⁷ McNutt, Ross, Lt Col, USAF, formerly Director, Air Force Cycle Time Reduction Office, interviewed at Los Alamos National Laboratory by author, 25 Feb, 2005.

⁸ R&D 100 Award, PREDICT a New Approach to Product Development, Los Alamos National Laboratory. LALP-99-184, August, 1999. On-line. Available at: http://www.stat.lanl.gov/projects/projects/Army/Section_1/R&D.pdf.

Chapter 3

Other DoD Acquisition Applications of PREDICT

Knowledge-based acquisition is a management approach which requires adequate knowledge at critical junctures (i.e., knowledge points) throughout the acquisition process to make informed decisions.

—DoD Directive 5000.1

The acquisition OODA Loop must be sped up significantly. Only changes that reduce cycle time should be incorporated. This section briefly looks at a number of other areas in the DoD acquisition process which PREDICT could be used to reduce cycle time. These areas include:

- Knowledge-based Acquisition.
- Concept Refinement.
- Test program development and execution.
- Documenting program history.
- Tracking system change.

Knowledge-based Acquisition

DoD Directive 5000.1 “calls for sufficient knowledge to reduce the risk associated with program initiation, system demonstration, and full-rate production.”¹ The directive goes on to say the following:

Implicit in this approach is the need to conduct the activities that capture relevant, product development knowledge. And that might mean additional time and dollars. However, knowledge provides the decision maker with higher degrees of certainty, and enables the program manager to deliver timely, affordable, quality products.²

To make a significant improvement, simply delete the sentence “And that might mean additional time and dollars.” Then add a statement at the end of the quote that reads “Any tools or processes incorporated should enable lower level decision-making to restore trust and initiative in the DoD Acquisition Process.” PREDICT enables the systematic capture of subject matter expertise / knowledge, early and throughout the acquisition process. This is the key to timely lower risk decision-making by the PM and the Milestone Decision Authority (MDA).

PREDICT at Concept Refinement

PREDICT could be implemented during Concept Refinement – for reference, the Defense Acquisition Management Framework is provided in figure one³.

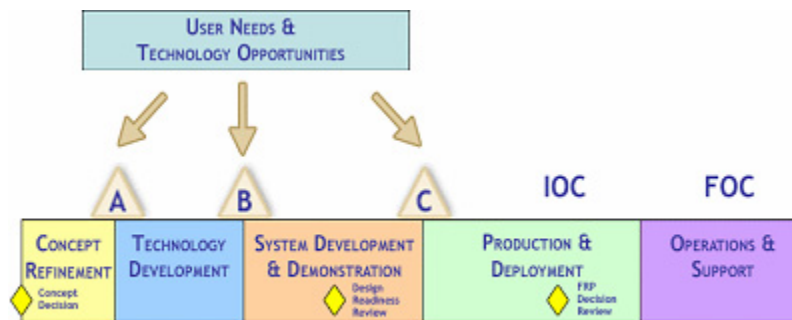


Figure 1 Defense Acquisition Management Framework

The purpose of the Concept Refinement Phase is to refine the initial concept and develop a Technology Development Strategy. Concept refinement is accomplished by conducting an Analysis of Alternatives (AoA) for the selected concept. This concept is identified in the Initial Capabilities Document which documents gaps in military capability. The AoA assesses critical technology maturity and risk associated with the selected concept to determine the best alternative to close the gap in military capability.⁴

The same systems engineers and designers that conduct the AoA could also feed the PREDICT process. The PREDICT team would conduct the elicitations and translate the expert knowledge into a reliability estimate. The focus at this level would be on the experts' knowledge and experience with the critical enabling technologies for the concept. PREDICT could also determine the impact to reliability from adding or deleting requirements to the system, which occurs frequently early in the acquisition process. This data would be included in the AoA results.

A search of the DoD Acquisition Guidebook (DoDI 5000.2) reveals the first time an actual estimate of reliability is currently required is in support of the Design Readiness Review, during the System Development and Demonstration Phase.⁵ PREDICT would move this forward significantly by supporting an estimate of reliability as exit criteria for the Concept Refinement Phase at the milestone A decision. PREDICT could uncover “asymmetric fast transients” the AoA team and / or the MDA could leverage to reduce the overall risk of the concept being successfully implemented for the warfighter.

Reduced Test Program Risk

PREDICT can also reduce risk in the development and execution of test programs. How? By highlighting challenging technologies and / or worst-case performance environments, noting where reliability is low and uncertainty is high. As shown in the example in Appendix C, PREDICT enables the test developer to focus limited resources on areas of concern or uncertainty. This enables better decision-making, just like a reconnaissance team locating enemy forces on the battlefield, so the commander has the knowledge to maneuver and seize the initiative. Further, with PREDICT, the PM can defend the test program by showing the impact to reliability and uncertainty if specific

tests are eliminated because of funding cuts, for example. Likewise, the PM can defend the need for additional testing by showing the impact to reliability if a specific test is added to the program.

Program History

Documentation is critical to successful implementation of PREDICT. The systematic capture and documentation of expert knowledge throughout the system lifecycle would be invaluable as personnel transition in and out of the program. This could be likened to the acquisition community's intelligence preparation of the battlefield. One can't make timely decisions without a solid knowledge of the program issues, past and present. The PREDICT database would be a ready source of information and history for current and new personnel to review the technical basis for previous decisions.

Why would PREDICT succeed where others have failed at providing an effective transfer of program history? The bottom-line is the "history" PREDICT provides is not just a history, it's a documented track record of system performance! In a typical program office, when the tasker arrives to provide the input to the history office, the boss looks around and tags the junior officer or civilian. The likely input is simply a timeline of events, without the technical information and data to backup the significant events and decisions. As discussed in Appendix B, PREDICT documentation must provide traceability giving the Who, What, When, and Why a given decision was made.

The documentation from a properly implemented PREDICT methodology will be in high demand. The MDA, PM, test developers, AoA study team members, and yes, the action officer building the history office input will all leverage this documentation.

System Change

As changes are made to fielded systems to meet the evolving needs of the warfighter or to address aging issues, PREDICT can be used to evaluate the changes based on system reliability impacts, again, reducing risk in decision-making. This applies to systems in which PREDICT was implemented at Concept Refinement, or when changes to a legacy system were being considered. Whether used on a new or legacy system, with PREDICT, reliability is continuously tracked as the system evolves providing a documented technical and reliability history of key program changes.

A key question to ask is whether or not PREDICT itself is reliable? Why should DoD consider a methodology without some assurance of success? Chapter four answers this question with a look at Delphi Automotive's application of PREDICT.

Notes

¹, The Defense Acquisition System, DoD Directive 5000.1, USD (AT&L), 12 May, 2003, paragraph 11.5. On-line. Available at:
http://akss.dau.mil/dag/DoD5000.asp?view=document&rf=GuideBook\IG_c11.5.asp

² Ibid, paragraph 11.5.

³ DoD Acquisition Guidebook, DoD Instruction 5000.2, USD (AT&L), 12 May, 2003, paragraph 3. On-line. Available at:
<http://akss.dau.mil/dag/DoD5000.asp?view=document&rf=DoD5002\Figure1.asp>.

⁴ Ibid, paragraph 3.5.

⁵ Ibid, paragraph 3.7.4.

Chapter 4

Commercial Application of PREDICT

"PREDICT allows our customers to leverage our company's greatest asset – the expert knowledge of our people."

—William S. Warren, Director of Engineering for Delphi Energy & Engine Management Systems¹

The commercial application of PREDICT is limited. The author was only able to find one commercial use of PREDICT, a Delphi Automotive fuel system application. Delphi worked in collaboration with LANL to develop PREDICT beginning in the mid-1990s for a period of approximately five years. Note that in 1999 LANL and Delphi were jointly recognized with an “R&D 100 Award” from R&D Magazine, a yearly recognition of the 100 most technologically significant products and processes.²

Delphi

Delphi's interest was driven by the major expense of product changes. One problem corrected during manufacturing cost \$300,000. If the problem was caught later and resulted in a recall, it could cost \$5,000,000.³ As discussed earlier, LANL's interest was in developing a methodology to combine expert knowledge with sparse test data to better calculate reliability of weapons undergoing change. This common interest led to Delphi working with LANL to develop the PREDICT reliability methodology.

In the commercial application, Delphi established teams throughout the world that focused on using PREDICT to improve a fuel injection system. Experts answered formalized questions in ranges that could be quantified and graphed using probability distributions, as discussed in the gas valve example (Appendix C). These distributions were combined using Monte Carlo simulations. The results focused testing on risky areas to improve reliability and reduce uncertainty. Without testing, engineers could answer “what if” questions about specific portions of the design to determine if a potential design change had a significant impact on reliability.⁴ The goal was to ask questions and make changes until the system met or exceeded the reliability requirement.

Reliability of PREDICT

How do we know the methodology works? For DOE weapons, system level tests cannot currently be performed to corroborate PREDICT estimates. Even if testing was allowed, the number of tests required to be statistically significant would very likely not be approved. However, at Delphi, tests were conducted and customer data was collected subsequent to the estimates made with PREDICT. Delphi set specific reliability goals for PREDICT related to fuel injection warranty work and product recalls. The data collected corroborated the PREDICT calculations prior to testing. This was not just one isolated example at Delphi. PREDICT was used on five concept Delphi systems.⁵

Unfortunately the use of PREDICT was not continued after a change of ownership at Delphi led to new leadership and management. As is always the case with new and innovative processes, a solid commitment from leadership is required to maintain momentum.

Notes

¹ Delphi and Los Alamos National Laboratory Receive Prestigious R&D 100 Award. The Auto Channel, 24 September, 1999. On-line. Available at:

<http://www.theautochannel.com/news/press/date/19990924/press000042.html>, 1.

² Ibid, 1.

³ R&D 100 Award, Los Alamos National Laboratory. LALP-99-184, August, 1999. On-line. Available at:

http://www.stat.lanl.gov/projects/projects/Army/Section_1/R&D.pdf.

⁴ Performance and Reliability Evaluation with Diverse Information Combination and Tracking, Program Treatment (text for Delphi DVD promo), 18 February, 1999, 5.

⁵ Booker, Jane M., Thomas R. Bement, Mary A. Meyer, William J. Kerscher. *PREDICT: A New Approach to Product Development and Lifetime Assessment Using Information Integration Technology*. Los Alamos National Laboratory document: LAUR-00-4737, May 2003, 5.

Chapter 5

Conclusions

An expert knows all the answers – if you ask the right questions.

—Author Unknown

After twenty years of reform initiatives, it's time to move beyond "the same stuff, only faster" approach to acquisition reform. Acquisition doctrine should be developed that feeds off our warfighting doctrine which calls for trust and initiative at all levels. The acquisition OODA Loop must be shortened by implementing decision tools like PREDICT to create "asymmetric fast transients." Decision tools emphasizing trust and initiative over documentation and process should be put in place. A DoD Acquisition Battlelab is one option to consider as a change agent for at least a ten-year effort to transform DoD acquisition to be truly agile, focused on the vision of filling Combatant Commander gaps in military capability in the shortest cycle time possible. The Acquisition Battlelab could also be the initial location for the equivalent of a "weapons" school for the acquisition special operators that are employed there.

The key to any acquisition reform initiative should be creating John Boyd's "asymmetric fast transients." Acquisition professionals need the ability to divert off unproductive paths immediately. Communications should move up and down the chain of command quickly, similar to the modern battlefield, with levels of acquisition

mirroring the tactical, operational, and strategic levels of war. The BLU-118/B case demonstrates we have the ability to be agile if motivated. Every delay in today's constipated acquisition process has a huge expense when one considers the marching army behind an acquisition effort. The DoD acquisition process is fighting the equivalent of WWI trench warfare when it should be engaged in the agile maneuvers of the Afghan and Iraq wars.

The PREDICT methodology could be one of the first experiments the Acquisition Battlelab applies. A number of potential applications for PREDICT in the DoD acquisition process were discussed:

- Shorten the TPIPTs and Modernization Planning processes.
- Enable assessment of reliability for new concepts at Milestone A and for legacy systems undergoing change, eliminating unproductive paths earlier.
- Optimize test planning and execution by showing testing impact to reliability.
- Enable transfer of knowledge as experienced personnel transition out of programs.

LANL and Delphi implemented PREDICT at the sub-system level. This may be the best approach for DoD to experiment with the implementation of PREDICT or other tools to create “asymmetric fast transients.” A system-level application would be a huge effort for any new decision tool. Legacy systems are continually undergoing change to address aging issues and to keep up with the evolving threat. A modernized guidance set, communications suite, or sensor, for example, would be prime candidates for the first use of PREDICT in DoD acquisition. This approach would start small and expand as the benefits of PREDICT or any new decision tools are proven.

It's time to lessen the burden on the acquisition corps. When considering cockpit design, a key issue is task saturation. The PM is beyond task saturation – that's why it takes twenty years to field next generation systems like the F/A-22 or SBIRS. The

motivation for change should be freeing up resources for other acquisition efforts supporting the GWOT. Shortened cycle time equates to fewer gaps in military capability.

Appendix A

Reliability Background

These appendixes are intended to provide a thorough discussion of how LANL is using the PREDICT reliability methodology. The key point for the application of PREDICT to reduce DoD acquisition cycle time is the idea of eliciting expert knowledge as a decision tool, when information is sparse.

Before looking at the PREDICT process and the example, Appendix A provides a technical foundation by describing mission reliability, uncertainty, key reliability equations, and Bayes' Theorem.

Mission Reliability

For “single-shot” systems like a bomb, mission reliability is specified¹ to define performance. Mission reliability is defined as “the probability that a system will perform mission essential functions for a period of time under the conditions stated in the mission profile.”² The stated reliability would apply for a specified period of time; for example, the life of the bomb, which could be 5, 10, or 20 years. The cost of poor mission reliability is additional sorties, increased operational costs, and greater potential for casualties.

Uncertainty

To determine the level of confidence in the reliability estimate, the amount of uncertainty must be determined. Uncertainty arises from two sources. The first is the scatter or variability of data resulting from actual tests. The second source of uncertainty reflects the expert's lack of knowledge, the things they don't know, or differences of opinion. Each expert, for example, will provide different responses based on their own set of assumptions gained from their life experiences.³

If a number of experts are asked the same question, there will be differences in their replies, just as there is variability in the results from running the same test multiple times. Using PREDICT, these differences in expert knowledge are analyzed just as if you were assessing test data results. Some experts will quantify their estimates with specific numbers or ranges. Others may use terms such as high or low, which are quantified with numbers such as a .9 or .1, for example, for use in calculations. Once the differences in expert knowledge are quantified, the mean and standard deviation are calculated. The reliability estimate is the mean, while the corresponding uncertainty is the standard deviation. A rule of thumb in reliability theory is to use two times the standard deviation or the 95 percent confidence interval for a conservative uncertainty estimate.⁴

How do you transition from uncertainty to confidence? Confidence can be thought of as inversely related to uncertainty, as shown with the blue line in figure two. If you have high uncertainty, there is low confidence in the reliability estimate (red line, figure two). Conversely, if you have low uncertainty, there is high confidence in the reliability estimate (green line, figure two).⁵ These terms sound straightforward, but the calculations to derive them can quickly become involved.

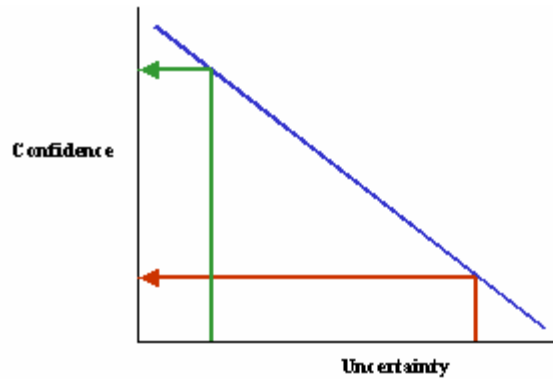


Figure 2 Confidence vs. Uncertainty

Calculations

The calculations for determining the reliability of a system are driven by how the subsystems are interconnected and their relationships to one another. A system structure can be depicted with a series model, a redundant (parallel) model or a mixed model. The following notes apply to the figures below which depict each of these models.

- Reliability formula and assumptions are shown for each model
- R_S = Reliability of the system
- R_i = Reliability of the i^{th} subsystem
- $Q_S = 1 - R_S$ = unreliability of the system
- $Q_i = 1 - R_i$ = unreliability of the i^{th} subsystem
- Π = Product of

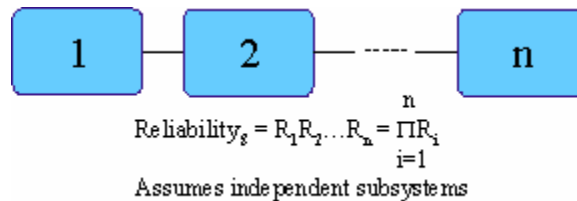


Figure 3 Series Model

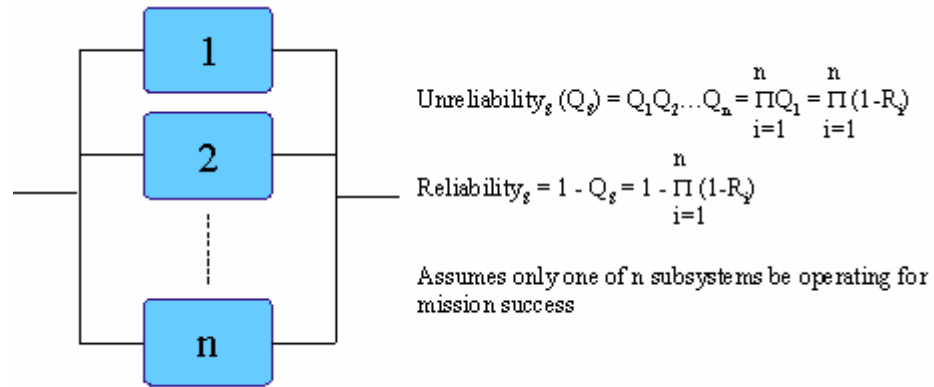


Figure 4 Redundant Model

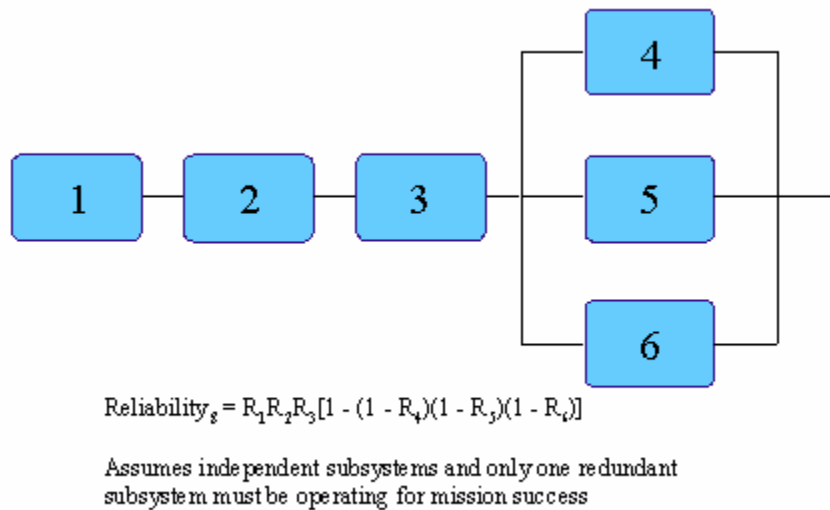


Figure 5 Mixed Model

These models reflect the simplest form of the system structures discussed. As noted in the figures, the models assume independent subsystems.⁶

How are uncertainty and confidence determined for the system? The reliability of each element in the model has variability, whether the data source was actual test results or expert knowledge. For each element, the mean and standard deviation are calculated

and then combined mathematically, using a Monte Carlo simulation, for example, to calculate the mean and standard deviation for the system.⁷

Monte Carlo simulation was originally developed for the Manhattan Project in World War II. The simulation uses random numbers and statistics to solve complex mathematical problems. For each variable being modeled, a probability distribution is assigned for the range of possible values. The simulation randomly generates values for the variables according to the distributions specified. The simulation is run over and over (i.e., 10,000 times) to generate an answer to the problem.⁸

Bayes' Theorem

How does PREDICT combine different sources of information, such as historical data, test data, and expert knowledge? A key information combination tool used in PREDICT is Bayes' Theorem, shown below.

$$\text{Prob (A|B)} = \text{Prob (A)} \text{Prob (B|A)} / \text{Prob (B)}$$

The Prob (A|B) is read as the probability of A given that B occurred. Likewise, Prob (B|A) is read as the probability of B, given A occurred. These two probabilities are conditional, meaning they measure the degree of plausibility of the event, given the other occurred. The probability of A and B (Prob (A) and Prob (B)) are unconditional probabilities in that they are not tied to the other event occurring or not occurring.⁹

Bayes' Theorem is used because it recognizes the value of mathematically combining prior information with new information (likelihood) to reduce uncertainty.¹⁰ In most cases, there is some prior knowledge (i.e., historical data) that can be quantified as a "prior distribution." A "likelihood distribution" is calculated from the elicitations, and combined with the prior distribution to form the "posterior distribution."¹¹ In a

successful effort, the posterior distribution should yield a higher reliability, with reduced uncertainty. This will be shown later in the example appendix.

With this technical foundation established, Appendix B will explain the PREDICT process steps required to calculate initial reliability (R_0).

Notes

¹ DoD 3235.1-H, "Department of Defense Test and Evaluation of System Reliability Availability and Maintainability-A Primer," March, 1982, 2-2.

² DoD 3235.1-H, 2-2.

³ Booker, Jane M., Los Alamos National Laboratory, interviewed by author, 20 January, 2005.

⁴ Ibid.

⁵ Ibid.

⁶ DoD 3235.1-H, 2-7.

⁷ Booker interview.

⁸ Bong, Duane, "Introduction to Monte Carlo Simulation." Vision Engineer. On-line. Available at: http://www.visionengineer.com/mech/monte_carlo_simulation.shtml.

⁹ Press, William H., Saul A. Teukolsky, William T. Vetterling, Brian P. Flannery. "Numerical Recipes in C," Cambridge University Press, New York, NY, 1992, 819.

¹⁰ Ross, Timothy J., Jane M. Booker, W. Jerry Parkinson. "Fuzzy Logic and Probability Applications: Bridging the Gap," ASA-SIAM Series on Statistics and Applied Probability, SIAM, Philadelphia, ASA, Alexandria, VA, 2002, 73.

¹¹ Meyer, Mary A., Jane M. Booker. Eliciting and Analyzing Expert Judgment. Philadelphia, Pennsylvania: American Statistical Association and the Society for Industrial and Applied Mathematics, 2001, xxi.

Appendix B

PREDICT – DEFINING THE PROCESS

PREDICT has been used successfully in automotive development and nuclear weapon physics packages. “The PREDICT application is a formal, multidisciplinary process for estimating the performance of a product when test data are sparse or nonexistent.”¹

Information Combination

PREDICT combines diverse information sources to determine performance or reliability of a product, and tracks that performance or reliability as the product changes or as additional data (test data, for example) becomes available. In the automotive industry, PREDICT has been used as a development guide before, during, and after prototyping and then documenting life cycle performance.² This was discussed in Chapter 4, Commercial Application of PREDICT.

The key contribution PREDICT brings to the table is the ability to “estimate reliability early in product development, before costly design and production decisions are made.”³ PREDICT pulls together all available information including expert knowledge, historical data, experience with similar products, and computer simulation. With PREDICT, these data sources are gathered and combined to produce reliability estimates early and through-out the product life cycle. PREDICT can provide accurate

reliability estimates at the engineering concept phase. As the product changes and / or as additional data become available, the PREDICT model can be updated to provide a life cycle track record of the product performance.⁴

PREDICT – What Is It?

A good first step is to state what PREDICT is not. PREDICT is not a management approach like Total Quality Management or an acquisition strategy like Spiral Development. Further, the implementation of PREDICT on a given development effort has not been boiled down to filling in the blanks in a checklist or software tool. On the contrary, PREDICT is a process, not a software tool or the latest acquisition reform buzzword. PREDICT captures expertise (knowledge) to determine product or concept performance early in the change or development process.

The PREDICT process is graphically displayed in figure six. The following discussion elaborates on the first four steps of the PREDICT process. These four steps yield the initial reliability estimate, (R_0). The remaining steps provide for reliability updates as new data become available through the product life cycle.

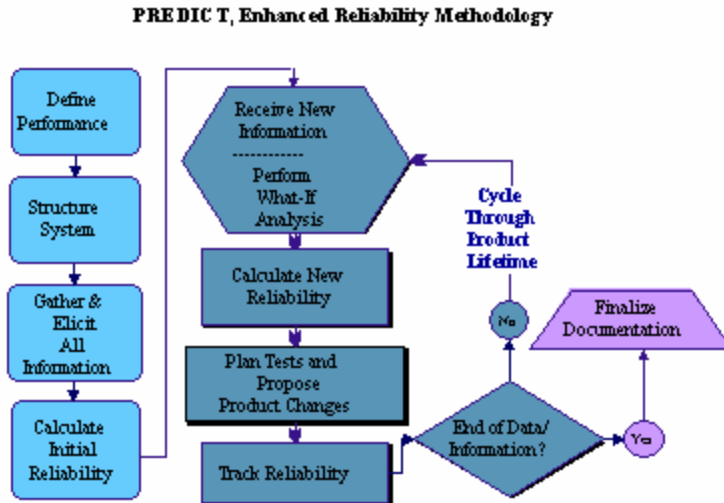


Figure 6 PREDICT Process⁵

Define Performance

Reliability is classically defined as the probability a system does not fail or functions properly.⁶ In common applications, the proper function of a part, subsystem, or system is defined in a specification. The PREDICT implementation must clearly define these specifications in language the particular industry understands. The specifications can vary greatly from material properties to the man-machine interface, for example. There will likely be multiple performance definitions that define the system performance. How does a team of statisticians and analysts accurately define the performance of complex systems and subsystems which are very likely unfamiliar to them?

A critical element in building the PREDICT team is to assign a small number of SMEs to the PREDICT team as “insiders,” (i.e., translators or advisors). Insiders provide detailed knowledge of the system or subsystem under review and insight on the jargon used by SMEs. Insiders are key experts who “provide entry into their culture of both other experts and management, explain its workings to analysts, provide guidance on

elicitation, and motivate wider participation by other experts.”⁷ Insiders have personal relationships drawn from years of experience working with the engineers and scientists whose knowledge is the linchpin of the PREDICT process. The insiders “bridge the gap” between the analysts and the SMEs, so the system performance can be defined in the language (or very likely the jargon) of the customer.

The PREDICT process systematically defines performance specifications in terms the engineers and designers understand. The SMEs’ knowledge and beliefs about the concept or system dating back to its origin, if needed, are documented for later analysis.

Structure System

During this step, a graphical representation of the system and the system performance is developed. This is done at the part, subsystem, and system level. Manufacturing processes, environmental conditions and failure mechanisms should also be included. Representations such as fault trees, fish bone diagrams and reliability block diagrams are constructed in a manner easily understood.

A key component of the structure is defining the interrelationships between the parts and processes. These interrelationships must be defined mathematically, based on knowledge gained through formal elicitation. To capture complex interrelationships between parts and subsystems, a logic-based model is used. The goal of a logic-based model is to provide a “diagrammatic representation of a complex set of processes and / or parts which depicts a logic flow between these constituents.”⁸

A number of methods are available to build a logic-based model – one or a combination of the examples listed below may be used.⁹ The key consideration should

be the ability of the model to define the complex interrelationship between the parts, sub-systems, and processes involved in the problem.

- Process trees – shows how one process flows into another
- Bayesian networks – incorporates prior knowledge to determine reliability
- Weibull model – graphical representation of a typical life cycle using a bathtub curve
- Probability networks – depicts the probabilities of various parts and processes interaction
- Directed graphic techniques – fault trees or decision trees which depict the flow of time or force, for example, through a problem

The bottom line is this step “includes the formulation of mathematical models and functional relationships that bind the parts, nodes, and levels of the system structure together.”¹⁰ Without a solid graphical depiction of the system, the PREDICT analyst is unable to determine where to begin and where to end. The system structure is the roadmap for the elicitation step.

Gather and Elicit Information

The work accomplished defining the system structure lays the foundation for this, the formal elicitation step. Once the structure is understood, expert knowledge is gathered to determine reliability and corresponding uncertainty for parts or subsystems prior to design or in the absence of test data. For each part or subsystem, PREDICT analysts use a systematic approach to determine the likelihood of all potential failure modes. The goal of PREDICT is to gather all we know, and determine how well we know it (the uncertainty). In sparse data situations, most of this knowledge comes from the SMEs.

Documentation

Although a “Finalize Documentation” step is listed last in the PREDICT process (figure 6), documentation is critical during all steps of the process. It is discussed here, after the elicitation step, because in order to accomplish the fourth step (Calculate Initial Reliability), data must be documented in a manner that allows the statisticians to do their work.

Whatever software or database package is used for documentation, it must provide traceability for decisions giving the Who, What, When, and Why a given decision was made. To date, no standardized software tool supports PREDICT. The potential applications are too diverse for a single tool to facilitate the process. Software tools are chosen from within the customer’s industry or business because of the familiarity a given team of engineers, for example, already has with their own tools. Whether defining the system structure or conducting elicitations, the PREDICT team should use documentation tools the customer is already familiar with, to the extent possible.

Calculate Initial Reliability

This step pulls together the results of the structure and elicitation steps. The models used for the structure are populated with reliability estimates (with uncertainty limits) from statistical analysis of elicitations, test data, historical data, and experience. For new systems, the data will come mostly from elicitations, while a legacy system undergoing change will use elicitations as well as applicable test and historical data and experience.

The output of this step is an uncertainty distribution for initial reliability. This becomes the baseline on which to build future updates as additional data from test, for

example, becomes available.¹¹ As shown in figure seven, the initial reliability will likely be projected below the requirement with large uncertainty.

Updating the Initial Estimate

The remaining steps in the PREDICT process (figure six) are accomplished as additional data / information become available. Results from developmental test and prototyping should generate new information which will most likely increase reliability while decreasing uncertainty, as shown in figure seven. A successful effort will enter production at or above the required reliability, within the uncertainty specified by the customer. The same progress can be tracked on a legacy system undergoing change (for example, a fielded missile system being upgraded with a new guidance package). Once the upgraded subsystem is fielded, data from operational testing, sustainment, and aging and surveillance activities can be incorporated into a PREDICT reliability calculation using Bayes' Theorem. Appendix C provides a detailed mock example of a PREDICT application.

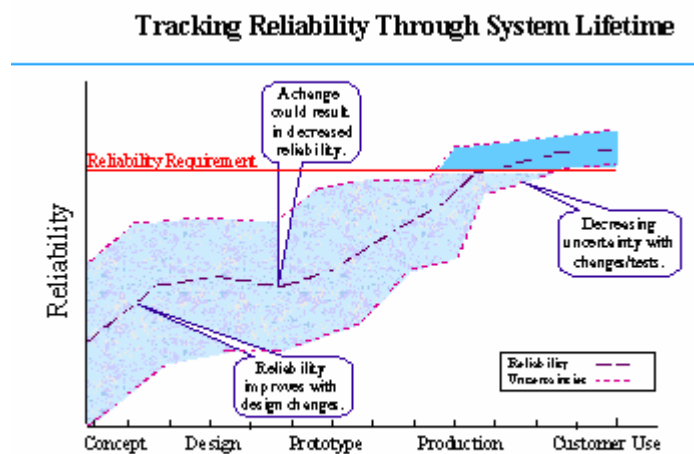


Figure 7 Reliability Through Life Cycle¹²

Notes

¹ Booker, Jane M., Thomas R. Bement, Mary A. Meyer, William J. Kerscher. PREDICT: A New Approach to Product Development and Lifetime Assessment Using Information Integration Technology. Los Alamos National Laboratory document: LAUR-00-4737, May 2003, 2.

² Ibid, 1.

³ Ibid, 1.

⁴ Ibid, 2.

⁵ Booker, Jane M., PREDICT – A New Approach to Product Development and Performance Prediction. Briefing from LAUR-99-6336 and LAUR-00-0543. October 2004, slide 6.

⁶ Booker, Bement, Meyer, Kerscher. LAUR-00-4737, 6.

⁷ Ibid, 6.

⁸ Booker, Jane M., email question response, November 2004, 1.

⁹ Booker, Jane M., email question response, November 2004, 1.

¹⁰ Booker, Bement, Meyer, Kerscher. LAUR-00-4737, 7.

¹¹ Booker, Bement, Meyer, Kerscher. LAUR-00-4737, 8.

¹² Booker, Jane M., PREDICT – A New Approach to Product Development and Performance Prediction. Briefing from LAUR-99-6336 and LAUR-00-0543. October 2004, slide 22.

Appendix C

PREDICT Example

The following example¹ demonstrates how to calculate an initial reliability (R_0), the fourth step in the PREDICT process (figure six). Also shown is the result of incorporating test data that was not available at the time of R_0 , generating an update, R_1 . The purpose is to illustrate how expert knowledge, combined with results from successful testing, yields a higher reliability estimate with less uncertainty. Note, this is a mock example, for illustrative purposes only.

Valve Operation

In this example, a new design is proposed for a valve assembly, whose function is to permit the flow of gas from a gas reservoir into another pressure vessel. Figure eight shows a diagram of the valve.

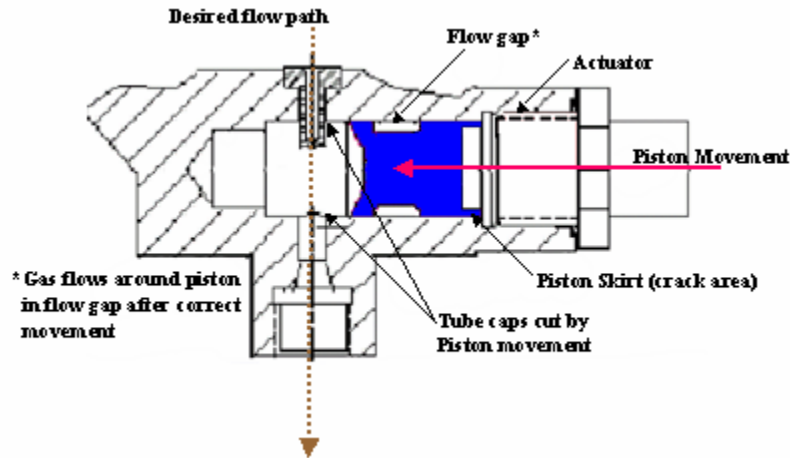


Figure 8 Gas Valve Cutaway

The valve functions by firing an actuator, an electro-explosive device which generates a high-pressure gas that pushes a piston down the inside of a cylinder. As the piston moves through the cylinder, it cuts two tube caps opening a channel for gas to flow from a reservoir to its desired destination. The rear of the piston is machined with a flared skirt at a specific angle. Upon assembly, this flared skirt is slightly deformed when it is pressed into the piston cylinder, thus providing a gas seal. If the piston functions properly, the skirt will maintain this gas seal through the entire range of piston motion. However, if the skirt cracks or becomes separated from the piston, an undesired gas path is created resulting in system failure. The valve assembly system structure has nine components of which all are in series, meaning all must function for the valve to work, as shown in figure nine. The reliability formula for the valve assembly is also provided in figure nine.

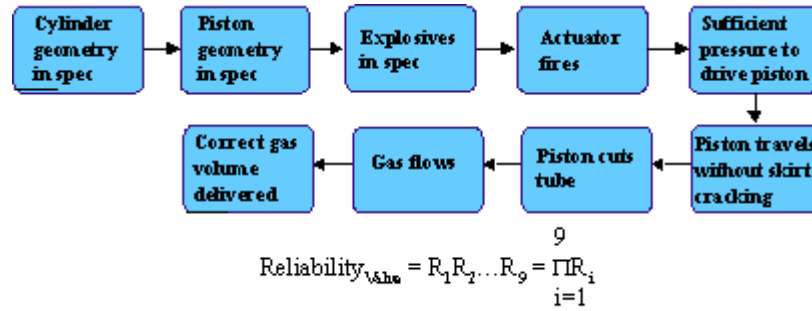


Figure 9 Valve Assembly System Structure

R_0 – Initial Reliability

In this example, initial reliability, (R_0) is calculated using existing data and expert knowledge. What is learned from R_0 will be used to guide the test program by focusing attention on areas where reliability is estimated as low and / or uncertainty is high.

In the valve assembly system structure (figure nine), the component of interest is the component labeled “piston travels without skirt cracking.” The probability of the piston not cracking (R_0 Piston) and the corresponding uncertainty will be calculated. The process for calculating the first reliability update (R_1 Piston) and its corresponding uncertainty will also be described.

The new piston design has several new features, but, to simplify the example, only the piston skirt angle will be considered. One reason for the new piston design is previous piston skirts were found cracked in fired (actuated) valve assemblies. As discussed above, a cracked piston skirt leads to system failure due to improper flow path. The cracks were found in pistons with certain skirt angles. Smaller skirt angled pistons in different valve assemblies showed no cracking, but these smaller angles are less desirable from a manufacturing standpoint.

Expert Elicitation

Knowledge about cracking and skirt angle behavior is not well defined, so obtaining reliability estimates for the new piston skirt angle had high uncertainty and relied upon expert knowledge from valve designers, production personnel, and engineering analysts who ran finite element mechanics codes on the piston. Experts in these fields were able to provide their estimates of piston performance for different skirt angles for this new system based upon their knowledge, previous data, and experience. These estimates were obtained in several elicitation meetings, which were one-on-one and face-to-face interviews with each expert. Separate interviews were held so one expert would not bias another.

Not all the experts agreed on the failure probabilities for given skirt angles. As shown in figure ten, the experts agreed up to a specific skirt angle there was a probability of 1.0 the piston skirt would not crack. Above this skirt angle the experts differed on the probability the piston skirt would not crack. This uncertainty region is shown in red in figure ten. The uncertainty region disappears at a higher skirt angle, where the experts once again agreed on the probability of the piston skirt not cracking. The proposed piston skirt angle, indicated by the blue dashed line, falls within this uncertainty region as illustrated in figure ten.

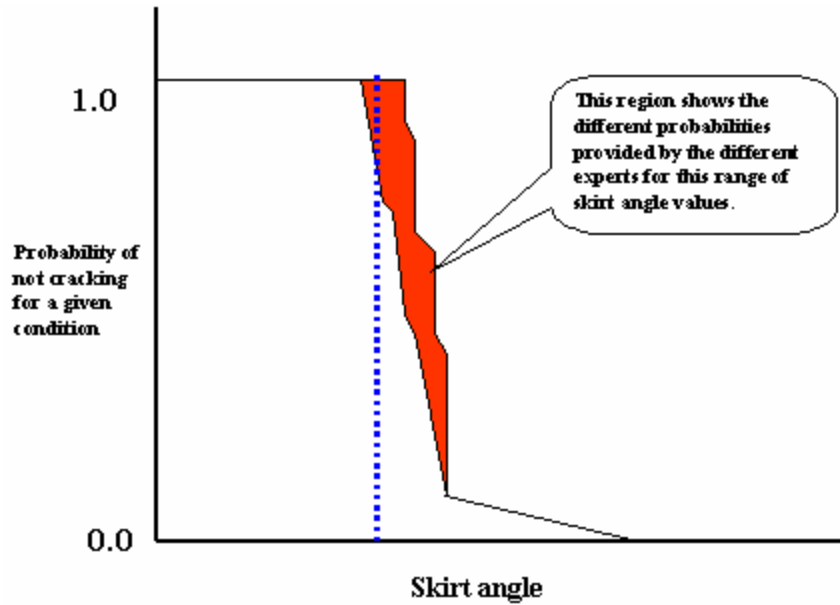


Figure 10 Skirt Angle Probabilities

$R_{0 \text{ Piston}}$ – Initial Reliability

From figure ten, the reliability interval for the desired skirt angle is roughly from 0.8 to 1.0. This is the lower and upper bound of the intersection of the blue dashed line with the red uncertainty region. This interval represents the probability of not cracking for a given condition (skirt angle), drawn from the knowledge of the experts. The experts agreed to use the Beta probability density function (PDF) in figure eleven to represent the likelihood the piston skirt would not crack in the interval from 0.8 to 1.0. The vertical axis of the PDF is not a probability but a density, which represents a relative likelihood of occurrence of each value along the horizontal axis. The figure eleven PDF curve shows the desired skirt angle is most likely to have a .97 reliability of not cracking.

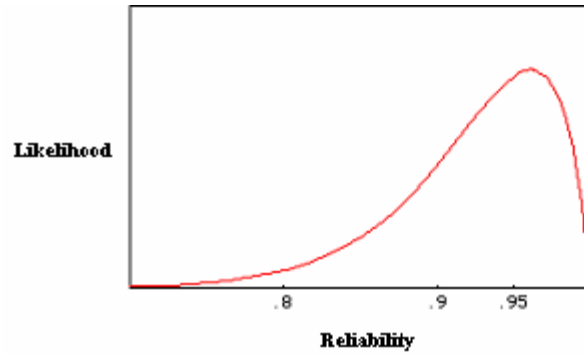


Figure 11 Beta PDF for Desired Skirt Angle

This same fitting of a PDF curve must be done for each of the potential skirt angles in the uncertainty region from figure ten. These Beta PDFs are combined or summed to generate the Beta PDF curve shown in figure twelve. The combination of distributions is done with a Monte Carlo simulation.

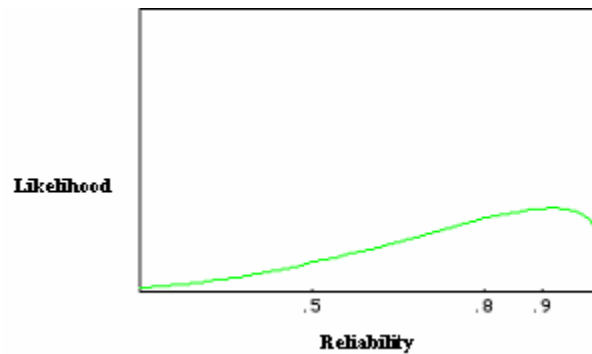


Figure 12 Beta PDF Summed Over All Skirt Angle PDFs

The mean for figure twelve is 0.73, with a standard deviation of 0.18. Doubling the standard deviation, this corresponds to a reliability range of [.36, 1.09]. Because the upper range is greater than 1.0, a 90 percent probability interval is used instead. This means 90 percent of the time, the reliability of the piston will be within the stated range. $R_{0 \text{ Piston}}$ equals 0.73, with a 90 percent probability interval for reliability of [0.37, 0.97]. The analysis of the knowledge from the SMEs yielded a low reliability with large uncertainty.

The same process would be followed to calculate the reliability and uncertainty of all nine components in the valve assembly system structure (figure nine). To determine the reliability of the valve assembly, a Monte Carlo simulation would be run to combine the reliabilities and uncertainties from each of the components of the valve assembly.

$R_{1 \text{ Piston}}$ – First Reliability Update

A test program was needed for the piston to increase the reliability estimate and decrease its associated uncertainty. PREDICT determined the desired piston skirt angle was within a region of uncertainty and focused the test program on the red zone in figure ten. Once data from the piston skirt angle test become available, $R_{0 \text{ Piston}}$ can be updated using Bayes' Theorem.

With Bayes' Theorem, the prior distribution ($R_{0 \text{ Piston}}$, green in figure twelve) is combined with the test data results. The test program resulted in five successes out of five trials. This yields a 90 percent confidence interval of [.63, 1.0], with a median value of 0.87. Median is used versus mean because the test data reflected a highly skewed (not symmetric) binomial distribution. Bayes' Theorem is now used to combine the prior distribution from the experts, with test data to generate the posterior distribution, $R_{1 \text{ Piston}}$ (blue in figure thirteen).

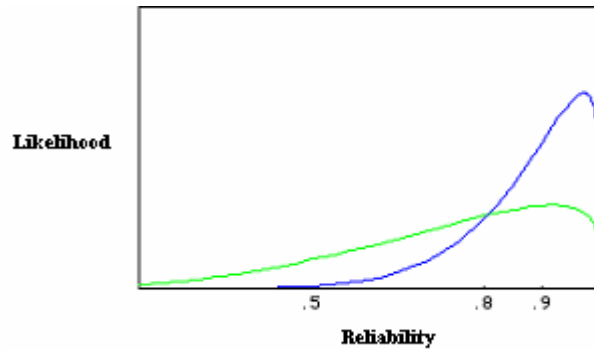


Figure 13 Beta PDF for Desired Skirt Angle

For $R_{1 \text{ Piston}}$, the mean is 0.87 with a 90 percent probability interval of [0.67, 0.99]. Combining the $R_{0 \text{ Piston}}$ with the test data increased the calculated reliability from 0.73 to 0.87 and the standard deviation decreased from 0.18 to 0.10. Likewise, the 90 percent probability interval, [0.37, 0.97], was improved to [0.67, 0.99]. This represents a significant improvement in reliability and reduction in uncertainty. Note that if some or all of the tests were failures, $R_{1 \text{ Piston}}$ would reflect less improvement or a reduction in reliability with corresponding impacts to uncertainty.

This example demonstrates the PREDICT contribution to assessing reliability. The early calculation of reliability documented the expert knowledge and focused the test program on an area of uncertainty in the gas valve design. The test program produced results consistent with the SME's knowledge leading to significantly improved reliability and reduced uncertainty.

Notes

¹ Booker, Jane M., Los Alamos National Laboratory, interviewed by author, 20 January, 2005.

Appendix D

Classified Report Access

For access to the B61-7, -11 Life Extension Program Reliability classified report, contact the LANL POC listed below to determine required clearance level and need-to-know.

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